

# Payload-Size and Deadline-Aware Scheduling for Time-critical Cyber Physical Systems

Marcus Haferkamp, Benjamin Sliwa, Christoph Ide and Christian Wietfeld

Communication Networks Institute

TU Dortmund University

44227 Dortmund, Germany

e-mail: {Marcus.Haferkamp, Benjamin.Sliwa, Christoph.Ide, Christian.Wietfeld}@tu-dortmund.de

**Abstract**—Compared to former mobile networks, Long Term Evolution (LTE) offers higher transfer speeds, significantly lower latencies and a widespread availability, qualifying LTE for a wide range of different applications and services in the field of conventional Human-to-Human (H2H) as well as fast growing Vehicle-To-X (V2X) and Cyber Physical Systems (CPS) communications. As a result, a steady growth of mobile data traffic, which is reflected in an increased interaction between different traffic classes, can be observed. In order to ensure timely transmissions of time-critical data in the future, we propose the novel Payload-Size and Deadline-Aware (PayDA) scheduling approach and compare its performance regarding the compliance for deadlines with those of other common packet scheduling mechanisms. The performance analysis is done with the complex and open-source LTE simulation environment LTE-Sim. The results show that the average latency can be reduced by the factor of 20 and the mean data rates can be enhanced by a factor of about 3.5 for a high miscellaneous data traffic. In the case of a heavy homogeneous and time-critical data traffic the mean Deadline-Miss-Ratio (DMR) can be decreased by about 35%.

## I. INTRODUCTION

In the course of the introduction of LTE and future 5th Generation Mobile Networks (5G) a wider range of new application types has been and will be established in mobile networks. Apart from the conventional voice and well-established mobile data communication, new use cases (e.g., in vehicular or smart grid environments) will lead to a constant growth of demands and utilization of the existing mobile network infrastructure, while at the same time focussing on the support of maximum data rates, a connection of a very huge number of devices and a highly reliable (timely) transmission of information. As a result of the interactions between the versatile applications and data traffic patterns, there is a negative impact on the compliance with Quality of Service (QoS) requirements during the transmission of data. The most important QoS-criterion for real-time applications is the adherence to time limits (deadlines). Within those deadlines time-critical data has to be transmitted in order to ensure the functionality of (safety-related) applications. While some existing real-time strategies propose to meet given deadlines, there are still no efficient techniques for mobile networks established which take deadlines as well as payload sizes into account. Resulting from this, there are many open research questions left which have to be solved to reach the targets of future 5G mobile networks. Hence, the focus of this paper is to propose a novel payload-size and deadline-aware scheduling

mechanism, inspired by the fundamental approach of the well-known Earliest Deadline First (EDF) scheduler, to close this gap. The EDF algorithm prioritizes data traffic only by means of deadlines, whereas crucial indicators, especially for mobile communications systems, like channel conditions, the amount of data to be transmitted and the fairness regarding the resource allocation are not considered at all. Fig. 1 exemplifies the prioritization of a User Equipment (UE) in a simple mobile cell scenario due to temporal requirements regarding the data transmission and the buffer size. The structure of this paper is as follows: First of all, the related work (e.g., real-time scheduling strategies) is discussed which is further followed by the presentation of the proposed PayDA scheduling strategy. In the next section, we introduce the simulation environment LTE-Sim [1] used to analyse the impact of the EDF and the proposed PayDA on various key performance indicators of data transmission (e.g., DMR and latency) for different data traffic patterns in LTE. Finally, detailed results of a simulation study are presented which clarify that the proposed PayDA scheduling scheme drastically reduces the average latency of data transmissions, while at the same time being at least as efficient as the EDF algorithm according to the DMR. As an overall conclusion, we outline that the results of this paper emphasise the need for a multi-criteria real-time scheduling strategy in mobile networks.

## II. RELATED WORK

In mobile communication networks, the role of scheduling schemes for data transmission is of prime importance for the

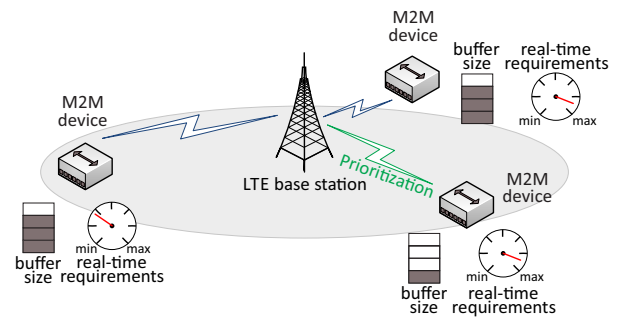


Fig. 1. Example scenario for prioritization of a UE concerning the allocation of spectral radio resources based on temporal requirements regarding the data transmission and the buffer size.

TABLE I  
COMPARISON OF DIFFERENT SCHEDULING ALGORITHMS: OBJECTIVES AND SCHEDULING CRITERIA

Scheduling algorithm	Optimization goals			Scheduling criteria		
	Max. Fairness	Max. Throughput	Adherence to deadlines	Deadlines	Packet size	Channel conditions
Round Robin	yes	no	no	no	no	no
Maximum Throughput	no	yes	no	no	no	yes
Proportional Fair	partial	partial	no	no	no	partial
Earliest Deadline First	no	no	yes	yes	no	no
Proposed PayDA	partial	partial	yes	yes	yes	no

performance efficiency of a system. Beside the challenges of wired communication systems, mobile communication systems have to accomplish additional effects regarding the users' mobility and thus permanently changing channel conditions. For this reason, there are many different resource scheduling mechanisms in LTE with manifold objectives (e.g., maximization of data rates [2], high degrees of fairness regarding allocated radio resources or achievable data rates [3]), which take the channel conditions in terms of the spectral efficiency into consideration. In case of real-time scheduling schemes it is possible to differentiate between two types of strategies: static and dynamic scheduling algorithms. Static scheduling mechanisms perform a prioritization of processes at the beginning of the actual scheduling procedure, whereas the dynamic ones are able to respond dynamically to new occurring processes at run time [4]. Due to the diversity of

respect to the M2M communication, in [10] a scheduling strategy is proposed that aims to be a trade-off between throughput maximization and satisfying given deadlines. There are also further suggestions for compliance with deadlines and channel conditions [11] and the buffer size of M2M users [12], respectively. In order to satisfy also deadlines of time-critical and heterogeneous CPS data traffic, this paper proposes a traffic-sensitive real-time scheduling algorithm and a performance comparison of the novel algorithm and the EDF. In contrast to the EDF that considers deadlines of processes exclusively, we merge this approach and the consideration of the data amount of each data transmission. The combination of these two aspects is introduced as PayDA scheduling scheme for mobile networks with the objective to enhance their efficiency in terms of the compliance with deadlines for a preferably high number of users.

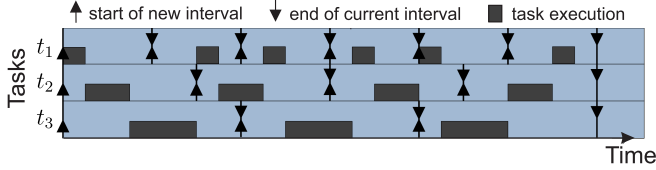


Fig. 2. Example of the functioning of the EDF scheduler for three tasks with various execution times and periodic deadlines

real-time and non-real-time scheduling strategies and various types of data traffic, multiple studies address the issue of the system performance for different traffic classes in LTE. In relation to the traditional H2H communication, the authors in [5] give a detailed overview of several types of common scheduling strategies and provide an assessment about the suitability of these procedures for use with different kinds of downlink data traffic in LTE. A novel, two-stage scheduling procedure with respect to QoS support in the downlink of LTE cellular network is presented and benchmarked for real-time data traffic [6] and also analysed for high-rate and time-critical multimedia data traffic [7], respectively. The simulation results of the proposed scheduling mechanism reveal quite low DMRs, but up to the factor of 3 lower data rates for best effort services than other common real-time schedulers. The increasing diversity of application types and operational areas in mobile networks leads to a growing contest to radio resources for data transmission. The resulting kinds of interdependences and influences on time-critical human-to-human applications caused by Machine-to-Machine (M2M) data traffic are discussed and a channel sensitive transmission scheme is presented as a solution approach in [8] [9]. With

### III. BASICS OF REAL-TIME SCHEDULING STRATEGIES

Before the proposed PayDA scheduling strategy is introduced in Sec. IV, its basis in the shape of the EDF and the fundamental basics of real-time scheduling schemes are discussed. Relating to real-time scheduling procedures, the adherence to deadlines of tasks is crucial, otherwise the system may fail with severe consequences to vary from harmless time-outs associated with retransmissions of dropped messages to system failures of a safety-relevant system. Therefore, different classifications of real-time systems and their deadlines are defined, reflecting the importance to meet time limits reaching from soft real-time systems to hard real-time systems. While in the former systems the violation of deadlines leads only to a degradation of the usefulness of the results, in the latter systems an injury of time requirements results in an overall system failure. In an environment of computing machines the feasibility of all time constraints can be calculated for  $m$  periodic tasks, of which the event  $i$  occurs with the period  $P_i$  and the calculation period  $C_i$ , as follows:

$$\sum_{i=1}^m \frac{C_i}{P_i} \leq 1 \quad (1)$$

If a real-time system meets this requirement, all events are schedulable and therefore no deadlines are going to be missed. Instead of the calculation period  $C_i$  in the surrounding of computers, the resource utilization of mobile networks can be used analogously. However, the only criterion of the EDF's approach is, as its name suggests, the remaining time to the deadline of each task. Fig. 2 illustrates the idea of the EDF scheme for three different tasks  $t_1$ ,  $t_2$  and  $t_3$ . The less time up

to a deadline is left the higher is the priority of a task. This approach is formulated as

$$\omega_i = \frac{1}{(\tau_i - D_{HOL,i})} \quad (2)$$

where  $\omega_i$  is the weight of a metric used for user prioritization,  $\tau_i$  is the deadline and  $D_{HOL,i}$  is the head-of-line delay for the  $i$ -th user. The head-of-line delay  $D_{HOL}$  marks the duration of stay of the first packet in a packet queue on the part of the transmitter since its generation. Further aspects like changing link qualities of mobile users due to frequency-selective channels conditions are not respected, because the EDF was originally designed for scheduling purposes in operating systems. Insofar the usage of this scheduling mechanism in its current form is not sufficiently applicable in mobile networks.

#### IV. PAYLOAD-SIZE AND DEADLINE-AWARE SCHEDULING FOR TIME-CRITICAL CYBER PHYSICAL SYSTEMS

As mentioned in the previous section, the application of the EDF scheduling algorithm is not suitable in mobile networks. The proposed PayDA scheduling scheme is an enhancement of the common EDF algorithm and extended by the consideration of the remaining data amount each user wants to transmit or receive. Hence, equation 2 has to be adapted to

$$\omega_i = \frac{1}{((\tau_i - D_{HOL,i}) \cdot \delta_{left,i})} \quad (3)$$

where  $\delta_{left,i}$  is the remaining data amount of the  $i$ -th user.

In order to delimitate the functionality of various popular scheduling techniques, Tab. I summarizes the objectives and scheduling criteria of the real-time scheduling mechanisms EDF and PayDA as well as of other common best effort scheduling strategies like Maximum Throughput (MT), Proportional Fair (PF) and Round Robin (RR). Obviously, in case of real-time data traffic it is more efficient to prefer multiple time-sensitive data streams with small amounts of data compared to a single comparable time-critical stream with a large volume of data. The proposed PayDA scheduling algorithm takes this assumption into account by considering both the remaining time to the deadlines and the need for rare radio resources for each user. By using the product of the data quantity and the remaining time to the deadline in the denominator of the fraction of Eq. 3 both values are of equivalent significance for the metric calculation. Therefore, a data stream with a close deadline and a small data amount tends to be preferred in contrast to data streams with either large data amounts or much time up to their deadlines.

The block diagram in Fig. 3 demonstrates the fundamental process steps of the proposed PayDA scheduler. The main focus of this scheduling procedure is on the metric calculation for each Resource Block (RB) and data traffic flow within a Transmit Time Interval (TTI) by using the formula of Eq. 3. After the metric calculation is finished, the RBs are allocated iteratively to the corresponding UEs according to their metrics. In this way, an efficient allocation of radio resources concerning the compliance with deadlines to time-sensitive data transmissions can be guaranteed. In addition

to the resource-efficient observance of deadlines, which is even possible with higher loads of the mobile networks, the PayDA mechanism also provides various configuration options in order to enable a fine granular control of spectral efficiency and fairness regarding the allocation of radio resources. As a result, further relevant aspects like channel conditions can be taken into account and various radio resource allocation strategies (e.g., only users with certain metric are considered) are possible.

#### V. SIMULATION-BASED SYSTEM MODEL

In this section, the simulation-based system model that is used for the performance evaluation of the proposed PayDA scheduling scheme is presented. It consists of the description of the actual LTE simulation environment with a scenario description and further data traffic classes in LTE.

##### A. Data traffic classes in LTE

Further types of mobile applications and their various requirements for data transmission have been added to LTE-Sim to reproduce a realistic and heterogeneous mobile data traffic in the simulation scenario. Tab. II provides an overview of the considered data traffic classes and the explicitly analysed applications. Apparently, both types of applications are examined: time-critical and time-tolerant ones. While several multimedia and safety-relevant services are among the former application type, applications in the field of CPS (e.g., smart meters) and convenience (e.g., web browsing) mostly belong to the latter group. Every mobile user runs only one application which start time is randomly chosen from a set of equally distributed values over the entire simulation time. All relevant information on the used applications (transmission interval, payload size, etc.) are also listed in Tab. II.

TABLE II  
TRANSPORT CLASSES ALONG WITH APPLICATION TYPES EXAMINED IN LTE-SIM

Data traffic class	Application type
H2H	web, video, voice
real-time V2X	safety-relevant (e.g., traffic report) convenience (e.g., multimedia)

##### B. LTE Simulation with Scenario Description

For evaluating and comparing the performance of the proposed PayDA scheduler with the EDF scheduling scheme, LTE-Sim simulator was modified and expanded with diverse application types proposed in the former section of this paper. In the simulation scenario, we use an urban environment to evaluate the performance of our proposed scheduling scheme. The scenario consists of one macro cell with a size of one kilometre and an increasing number of users using the Manhattan mobility algorithm for movement. Tab. III gives an overview of the most important simulation parameters for the proposed close-to-reality urban environment. Over and above the simulation parameters of the urban scenario, Tab. IV lists the parameters of all involved applications used to generate heterogeneous data traffic. In particular, the

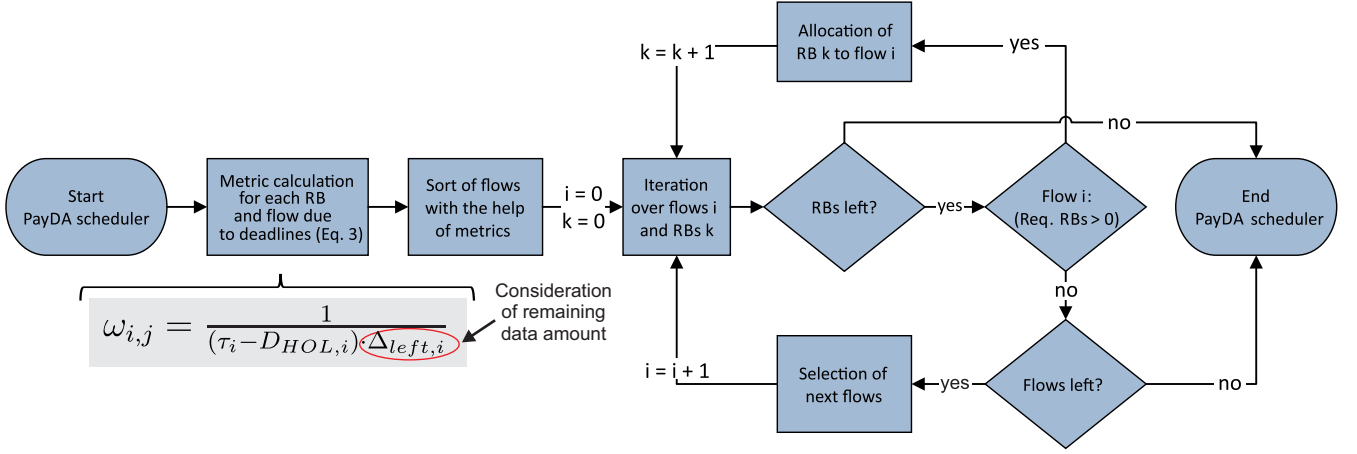


Fig. 3. Block diagram of the iterative process steps of the proposed PayDA packet scheduler: in each iteration the current resource block  $k$  is allocated to the user equipment corresponding to the data traffic flow  $i$  with the currently highest metric

data traffic generated by these applications has various time-critical and volume-oriented requirements for data transmission. Finally, the performance of both scheduling mechanisms should also be examined for a worst case scenario, where two applications with almost identical timing requirements but significant miscellaneous payload sizes are used for the generation of data traffic (Tab. V). Referring to this, two applications in the field of safety-relevant, time-critical and high-rate vehicular applications are chosen. Apart from the existing Context Awareness Messages (CAM) application, a fictional but realistic future application is chosen. Obviously, both applications define comparable timing requirements for data transmission but differ significantly from each other with regard to the transmission interval and the resulting data rate.

TABLE III  
PARAMETERS FOR THE SIMULATION OF A REALISTIC URBAN SCENARIO IN LTE-SIM

Simulation parameter	Value
Cell radius	1 km (Urban)
System bandwidth	20 MHz (100 Resource Blocks)
Operating Frequency	2.6 GHz
Channel model	Typical urban 3GPP
Max. RF power (Evolved Node B)	40 dBm
Max. RF power (User Equipment)	23 dBm
Number of User Equipments	50-130 (incrementally increased)
Total simulation period	100 seconds
Start times of applications	Equally distributed
Mobility	Manhattan mobility

## VI. RESULTS OF PERFORMANCE EVALUATION

We primarily compare the performance of the PayDA scheduling procedure with the one of the EDF scheduling strategy: The EDF just accounts for the remaining time to a deadline, whereas the proposed PayDA scheduler also respects the remaining payload for data transmission. In this regard, two types of data traffic are examined. At first, in Sec. VI-A a heterogeneous data traffic is analysed (Tab. IV), hereinafter in Sec. VI-B the performance of both scheduling mechanism is evaluated for a homogeneous data traffic (Tab. V).

### A. Urban scenario with heterogeneous data traffic

Fig. 4 illustrates the performance results of both real-time scheduling procedures and a selection of further common non-real-time scheduling algorithms (MT, PF, RR) in relation to the DMR and the latency for a heterogeneous data traffic generated by applications listed in Tab. IV. It should be noted that a comparatively high number of 80 mobile users who generate the interfering File Transfer Protocol (FTP) data traffic are taken into account. The left side of Fig. 4 reveals an optimal performance of both real-time scheduling algorithms regarding the DMR. In this case, considerably less than 1% of all scheduled data packets cannot be transmitted within the given deadlines. Compared to these values, the DMRs of the procedures MT, PF and RR are remarkably high with maximum values by about 30% up to 60%. The reason for the low performance of these scheduling algorithms is a variety of objectives, partially disregarding timing requirements completely. Therefore, the use of the latter scheduling mechanisms for time-critical data transmissions is not suitable. On the right side of this figure the overall latencies of all packet transmissions for those scheduling schemes are illustrated. In contrast to the analogue DMRs, now a significant difference of up to 14 seconds regarding the median latencies can be determined for the benefit of the proposed PayDA scheduler compared to

TABLE IV  
APPLICATION PARAMETRIZATION USED FOR SIMULATING AN URBAN SCENARIO WITH HETEROGENOUS DATA TRAFFIC IN LTE-SIM [13] [14]

Application	Max. delay [s]	Payload [Byte]	Interval [s]	Data rate [kbit/s]
VoIP	0.1	32	0.02	12.8
Video (H.264)	1	var.	0.4	242
Video call (High Quality)	0.2	var.	-	500
Video call (High Definition)	0.2	var.	-	1500
Music (MP3)	0.05	52	0.003	-
Website	10	$5 \cdot 10^3$	-	-
File Transfer Protocol	60	$5.25 \cdot 10^6$	30	-

the EDF algorithm. Even the use of the MT leads to an about 9 seconds lower median, whereas the application of the RR and PF schedulers results in a slightly higher median latency. This discrepancy of significantly diverging latencies of both real-time scheduling procedures results from the heterogeneous patterns of the data traffic generated by various applications in the field of H2H and V2X communications. While the vast majority of the examined H2H applications generate high-rate and time-critical data traffic (e.g., Voice over IP (VoIP) communication or music streaming) with small payloads, the interfering V2X data traffic is characterized by large and time-tolerant FTP data packets. This mixture of complementary properties and requirements could not be handled efficiently by the EDF scheduling strategy due to its exclusive consideration of deadlines. Therefore, the small-sized and time-critical H2H data packets are predominantly preferred compared to the time-tolerant FTP data packets regardless their remaining payload. As long as time-critical data packets are scheduled, all radio resources are used for their transmission even if there is only a small part of FTP payload left over. The proposed PayDA scheduling algorithm enlarges the efficiency of the scheduling procedure by additionally considering the remaining size of each scheduled payload. Insofar, also the priority of time-tolerant and primary large amounts of data for transmission increases incrementally, despite their deadlines that might be in the distant future. Another advantage of the

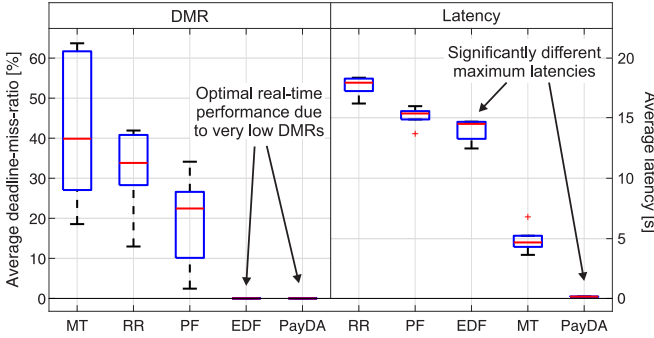


Fig. 4. Heterogeneous data traffic scenario: Comparison of average DMRs and mean latencies for various scheduling strategies. Proposed PayDA achieves lowest average DMR and latency.

PayDA scheduling strategy contrary to the EDF procedure is a higher average user data rate. Fig. 5 contrasts the differences of the average user data rates for both scheduling algorithms and the previously mentioned common scheduling strategies. Obviously, in this scenario a reduction in the average latency results in an enlargement of the mean data rates of all users. While a large dispersion of the data rates can be determined for the EDF scheduler, a significantly lower one can be noted in the case of the proposed PayDA scheduling procedure. This result can be easily explained by taking a closer look on the increase in the number of mobile users and thus the interfering data traffic in Fig. 5. Apparently, the increase in the number of interfering users has diverging impacts on the developing of the average user data rates. While the average user data rates initially increase by using the procedures EDF, PayDA

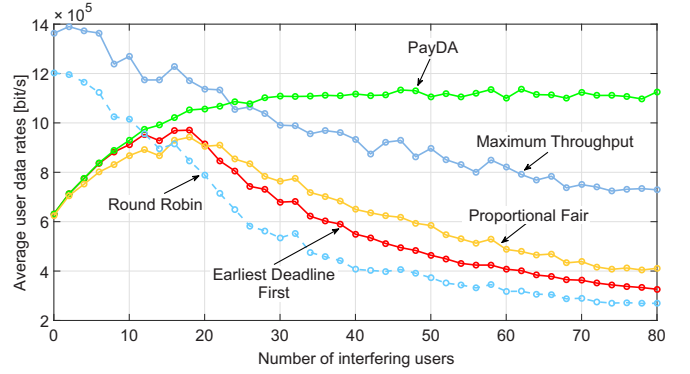


Fig. 5. Heterogeneous data traffic scenario: Analysis of the overall average user data rates for an increasing interfering data traffic when using different scheduling algorithms

and PF, they drop continuously if the strategies MT and RR are used. At a count of less than 20 interfering users, also the average user data rates start to decrease when using PF or EDF, whereas only the use of the proposed PayDA scheduling mechanism results in further increasing mean user data rates. Considering the highest level of interfering data traffic at a number of 80 mobile users, the average user data rates are larger by a factor of about 3.5 when using PayDA compared with those of the EDF scheduler. In addition, the mean user data rates differ by a factor of about 1.5 when using PayDA and the procedure with the next highest user data rate (MT). This issue is thus, that the PayDA scheduling scheme also allocates free radio resources to the time-tolerant and large-sized FTP data streams which are an integral part of the total amount of data to be transferred. In contrast, the remaining strategies have other objectives and therefore prefer other users for data transmission. For example, the EDF disadvantages those data streams because of their less strict deadlines. Hence, only the time-critical and high-rate but mostly small-sized H2H data streams form the transmitted data. The more interfering users want to transfer their FTP data, the greater this decreasing effect on the average user data rates will be. However, the collapse of the user data rates when using MT and RR is due to the preference of users with good channel conditions or the objective to reach a maximum level of fairness regarding the resource allocation, respectively. In both cases users with time-critical data transmissions are disadvantaged resulting in an increasing DMR which in turn leads to increasing drop rates in the sender's buffer. Consequently, high drop rates result in decreasing user data rates.

#### B. Urban scenario with homogeneous data traffic

For a nearly homogeneous data traffic generated by two time-critical and high-rate vehicular applications listed in Tab. V, Fig. 6 shows the DMRs of the EDF and the PayDA scheduler. In addition, various time intervals with different sizes and equally distributed values are used for the start times for data transmission of all application instances. Obviously, the temporal compactness of the start times has an impact on the DMRs for both scheduling algorithms. With an increasing dispersion of the start times, the rates take off when using both



TABLE V  
APPLICATION PARAMETERS FOR AN URBAN SCENARIO WITH  
TEMPORALLY HOMOGENEOUS DATA TRAFFIC IN LTE-SIM [15]

Application	Max. delay [s]	Payload [Byte]	Interval [s]	Data rate [kbit/s]
Context Awareness Messages	0.1	100	0.1	1
Future time-critical application	0.1	10000	1	10

strategies. Nevertheless, large differences in the performance are revealed particularly for small intervals. On this point, the proposed PayDA scheduling algorithm is considerably predominant with a gain by more than 35% with regard to the maximum DMR. With an increasing size of the start times interval the difference between the maximum DMRs is reduced to 25% (1 second interval) or is even negligible (100 seconds interval), respectively. The reason for this decreasing divergence of the maximum DMRs results from a lower density of data traffic, because applications like web browsing and especially FTP have limited payload sizes and therefore they only need a specific time period for data transmission.

The results presented before compare the mean values of the DMR, the latency and the user data rate of all active users when using different scheduling schemes in the given scenario. Apparently, the performance of all examined scheduling schemes varies with the intensity and type of data traffic.

## VII. CONCLUSION

In this paper, we have quantified the performance of various scheduling algorithms regarding the compliance of deadlines for time-critical data traffic with the help of a complex LTE simulation environment. In addition, we proposed the efficiency and performance improved PayDA real-time scheduling scheme. This scheduler seizes the concept of the EDF scheduler but extends it by the consideration of the remaining payload size of each data stream. The increase of the efficiency and the performance have been evaluated by means of a simulation-based system model. According to the presented results, the proposed scheme leads to significantly

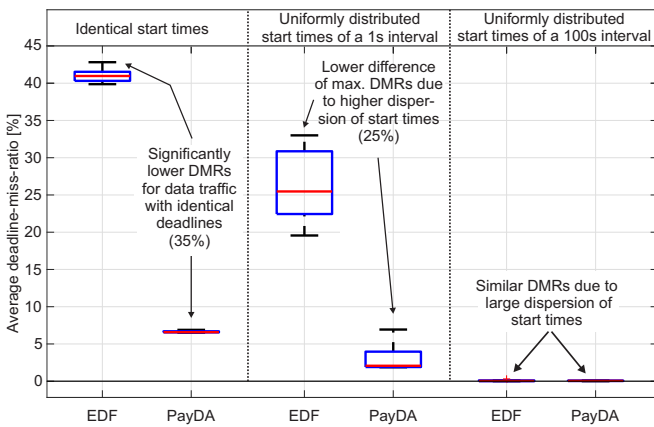


Fig. 6. Homogeneous data traffic scenario: Performance of PayDA in relation to EDF when using different start time intervals

lower latencies and higher user data rates at comparable low DMRs for homogeneous data traffic. In the case of (nearly) time homogeneous data traffic, especially the start times of the applications are relevant. At this juncture, the proposed PayDA scheduling strategy clearly predominates for very similar start times of various data transmissions. In the future, we will evaluate the PayDA scheduling strategy for other types of data traffic including further Machine-Type Communication (MTC) or vehicular applications.

## ACKNOWLEDGMENT

Part of the work on this paper has been supported by Deutsche Forschungsgemeinschaft (DFG) within the Collaborative Research Center SFB 876 "Providing Information by Resource-Constrained Analysis", project B4.

## REFERENCES

- [1] G. Piro, L. A. Grieco, G. Boggia, F. Capozzi, and P. Camarda, "Simulating LTE cellular systems: an open-source framework," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 2, pp. 498–513, Feb 2011.
- [2] W. Rhee and J. M. Cioffi, "Increase in capacity of multiuser OFDM system using dynamic subchannel allocation," in *Vehicular Technology Conference Proceedings, 2000. VTC 2000-Spring Tokyo. 2000 IEEE 51st*, vol. 2, 2000, pp. 1085–1089 vol.2.
- [3] J. G. Choi and S. Bahk, "Cell-throughput analysis of the proportional fair scheduler in the single-cell environment," *IEEE Transactions on Vehicular Technology*, vol. 56, no. 2, pp. 766–778, March 2007.
- [4] H. Chetto, M. Silly, and T. Bouchentouf, "Dynamic scheduling of real-time tasks under precedence constraints," *Real-Time Systems*, vol. 2, no. 3, pp. 181–194, 1990. [Online]. Available: <http://dx.doi.org/10.1007/BF00365326>
- [5] F. Capozzi, G. Piro, L. A. Grieco, G. Boggia, and P. Camarda, "Down-link packet scheduling in LTE cellular networks: key design issues and a survey," *IEEE Communications Surveys Tutorials*, vol. 15, no. 2, pp. 678–700, Second 2013.
- [6] G. Piro, L. A. Grieco, G. Boggia, and P. Camarda, "A two-level scheduling algorithm for QoS support in the downlink of LTE cellular networks," in *Wireless Conference (EW), 2010 European*, April 2010, pp. 246–253.
- [7] G. Piro, L. A. Grieco, G. Boggia, R. Fortuna, and P. Camarda, "Two-level downlink scheduling for real-time multimedia services in LTE networks," *IEEE Transactions on Multimedia*, vol. 13, no. 5, pp. 1052–1065, Oct 2011.
- [8] C. Ide, B. Dusza, and C. Wietfeld, "Client-based control of the interdependence between LTE MTC and human data traffic in vehicular environments," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 5, pp. 1856–1871, May 2015.
- [9] C. Ide, B. Dusza, M. Putzke, C. Müller, and C. Wietfeld, "Influence of M2M communication on the physical resource utilization of LTE," in *Wireless Telecommunications Symposium (WTS), 2012*, April 2012, pp. 1–6.
- [10] A. Elhamy and Y. Gadallah, "BAT: A balanced alternating technique for M2M uplink scheduling over LTE," in *2015 IEEE 81st Vehicular Technology Conference (VTC Spring)*, May 2015, pp. 1–6.
- [11] G. Piro, L. A. Grieco, G. Boggia, and P. Camarda, "A two-level scheduling algorithm for QoS support in the downlink of LTE cellular networks," in *Wireless Conference (EW), 2010 European*, April 2010, pp. 246–253.
- [12] N. Afrin, J. Brown, and J. Y. Khan, "Performance analysis of an enhanced delay sensitive LTE uplink scheduler for M2M traffic," in *Telecommunication Networks and Applications Conference (ATNAC), 2013 Australasian*, Nov 2013, pp. 154–159.
- [13] M. Kihl, K. Bür, P. Mahanta, and E. Coelingh, "3GPP LTE downlink scheduling strategies in vehicle-to-infrastructure communications for traffic safety applications," in *Computers and Communications (ISCC), 2012 IEEE Symposium on*, July 2012, pp. 000 448–000 453.
- [14] Skype, <https://support.skype.com/en/faq/FA1417/how-much-bandwidth-does-skype-need>, Skype Std.
- [15] C. Lottermann, M. Botsov, P. Fertl, and R. Müllner, "Performance evaluation of automotive off-board applications in LTE deployments," in *Vehicular Networking Conference (VNC), 2012 IEEE*, Nov 2012, pp. 211–218.